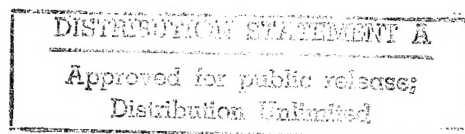MIT

APPLICABILITY OF LINEAR ELASTIC FRACTURE MECHANICS TO RIGID PVC PIPE MATERIALS

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by

A.Y. Darwish
J.F. Mandell
F.J. McGarry

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School of Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

INTRODUCTION

Pressurized plastic pipes for water and natural gas distribution are a prominent example of the increasing use of plastics in engineered structural applications. As such, they require careful design for properties such as stiffness and strength. Designs are typically limited by the stress-rupture curve, which defines the stress level the material can withstand for long time periods without a creep-rupture type of ductile failure (1). Under certain conditions, most plastics can also fail in a brittle mode, and this is well known for the PVC (polyvinylchloride) pipes investigated in this study (2). As will be shown, brittle failures are more likely to occur in the presence of large flaws, and under low temperature or high rate conditions.

The brittle fracture of PVC and other plastics has received increasing attention (3-7). Although difficult to use as a design parameter in all but the most sophisticated cases, brittle fracture properties of plastics may be of practical importance in choosing between different materials, and in formulating improved plastics. Many of the techniques of brittle fracture study have been adopted from metals technology. Consideration of the particular yield phenomena and viscoelastic characteristics of plastics has also been developing (3-6). Among the topics which have not been given sufficient attention for plastics is the validity of fracture toughness test results.

The theoretical basis of most brittle fracture studies is linear elastic fracture mechanics (LEFM) (8). The central assumption of LEFM is that the failure process at the crack tip occurs

under the control of the stress intensity factor, K_I, which characterizes the intensity of the stress field very close to a sharp crack tip. This assumption is approximately correct only as long as the initial crack tip is very sharp, and any yielding at the crack tip is localized within the region where the stress field is dominated by K_I. If the test conditions are such that the assumptions of LEFM are satisfied, then a critical value of K_I for unstable crack extension, K_c, can be determined, which represents the fracture toughness of the material. For sufficiently thick specimens the mode of crack growth is almost entirely opening, termed Mode I, and most of the crack front experiences plane strain conditions, so that the value of K_c is designated K_{Ic}, the plane strain fracture toughness (9).

VALIDITY OF FRACTURE TOUGHNESS TESTS

A fracture toughness test is conducted by preparing a test specimen of the desired geometry, containing a sharp crack. The specimen is then loaded to produce unstable crack extension. The fracture toughness, K_c, is determined by calculating the value of K_I at the load which produced unstable growth. This calculation may be carried out for any test without knowledge of the validity; unless gross ductility is evident, it is not obvious whether the test is valid. Many brittle-appearing fractures are in fact not only invalid, but follow a ductile, notch-insensitive failure criterion. The ductility need only extend ahead of the initial crack front over a region on the order of 10-20% of the crack length to produce this effect.

The most straightforward method of determining the validity
of a K_c value is to test specimens of different size and geometry.
If K_c is a valid material property, it should be invariant as long
as the same mode of growth is maintained. This approach to deter-
mining validity is tedious, but is used to justify more convenient
methods. A standard test method for the plain strain fracture tough-
ness, K_{Ic}, of metals has been developed by ASTM, designated E399.
This method is restricted to two geometries, compact tension (CT)
and three point bend (TPB). The validity of tests is determined as
follows:

1. The initial crack is made sufficiently sharp by precrack-
    ing in fatigue at a low value of K_I prior to the fracture
    toughness test.

2. The force used in calculating K_I at fracture is determined
    from a force vs. crack opening displacement (COD) curve so
    as to give the load corresponding to a 2% increase in crack
    length. This curve is also used to reject tests which sus-
    tain subsequent loads more than 10% higher than this value.

3. The quantity $S=2.5 (K_Q/\sigma_y)^2$ must be less than the crack
    length, thickness, and other specimen dimensions. K_Q is
    the candidate value of fracture toughness calculated from
    the load in (2), and an analytical expression of K_I in terms
    of the specimen geometry (K-calibration); σ_y is the yield
    stress in uniaxial tension at the corresponding rate and
    temperature. If S is too large compared with specimen di-
    mensions, a larger size must be used and retested.

In combination with details such as specimen dimension tolerances and crack plane orientation, the above conditions work well for a wide variety of metals. For polymers, the same general concerns must be addressed: crack sharpness, fracture load, and specimen size. The establishment of a standard test for polymers was beyond the scope of this study. However, the general significance of the validity question has been addressed for some limited cases.

EXPERIMENTAL METHODS

Materials and Specimen Preparation

The material used in this study was modified PVC from pipes used in pressurized water distribution. The pipes were obtained in various sizes from commercial sources as part of a more general study. The pipe sizes and classifications are given in Table 1. Although specimens taken from different pipes behaved in a generally similar manner, differences in yield strength and other properties were determined. Each series of tests for the study of rate or size effects used specimens cut from a single pipe, and so was self-consistent.

Flat test specimens were obtained by slitting the pipes lengthwise and flattening under slight pressure at 85°C, the glass transition temperature. This procedure changes the time-temperature history of the material significantly, but was necessary in order to use standard test specimens. Tests on unaltered pipes and sections of pipes are also being carried out as part of the general study, but are not reported here. Most of the tests in this study were on double-edge-notched tension (DEN) specimens. Three point

bend specimens (TPB) with a single notch were used for convenience for the study of crack tip radius effects. Specimen dimensions are given in Table 2.

Notches were cut with a slotter having an edge angle of 60°. This was followed by sharpening with a razor knife blade forced into the notch root to a controlled depth in a testing machine. The blades used were specially ground to an edge angle of 8-10° to produce sharper crack tips. The length of the razor sharpened region was approximately 10% of the notch length. This blade precracking procedure was justified by comparison with experimental results for other precracking methods as will be discussed later.

Test Procedure and Data Reduction

Tests were conducted on a servohydraulic machine at a constant rate of displacement. Most testing was done in an air conditioned laboratory without humidity control. The DEN specimens were loaded with wedge-action grips, while the TPB specimens were supported on freely rotating rollers of 6.4 mm radius. When recorded, crack opening displacement was determined with a gage similar to that given in the ASTM standard, but with a higher displacement capacity.

It was originally planned to record the load-COD curve for each test. However, the only valid tests were those at high rate, where recordings were made using an oscilloscope. Oscilloscope recordings do not have the resolution necessary for application of the 5% secant method of fracture load determination used in the ASTM standard. For those otherwise valid cases which were recorded, the fracture load determined by the 5% secant method was approxi-

mately equal to the maximum load, and the validity of the tests
was not limited by the load-COD curve conditions. For most of
the results reported, no load-COD curve was recorded. The frac-
ture load was taken as the maximum load, which was recorded on a
digital read-out module.

The value of K_I at fracture was calculated from the maximum
load and the calibration given in ASTM standard E399 for the TPB
specimens or that given in Ref. (10) for the DEN specimen. The
resulting value of K_I at fracture was designated K_Q, indicating
that it was a candidate value for K_{Ic}. The validity was then
tested by comparing the quantity S to the specimen dimensions

$$S = 2.5 (K_Q / \sigma_y)^2 < B, c \qquad (1)$$

where B is the thickness and c is the initial crack length. Tests
which satisfy Eq. (1) appear to be valid, and so K_Q was then des-
ignated K_{Ic}. It should be noted that this does not correspond ex-
actly to the ASTM E399 definition of K_{Ic}, since that standard is
for metals. Furthermore, the crack tip sharpening, fracture load
determination, and specimen geometry in the case of DEN specimens,
do not conform to the test standard. The validity condition used
here was confirmed by testing specimens of different sizes.

RESULTS AND DISCUSSION

Precracking Method

The first requirement of a valid fracture toughness test is that the crack be as sharp as a naturally occuring crack. For metals, precracking is done by fatigue crack growth at a maximum cyclic K_I value of not more than 60% of K_Q (E399). A common convenient method of precracking polymers is by use of a razor blade (3-7). Figure 1 compares the K_Q values calculated for several precracking methods. The crack tip radii could not be measured for fatigue precracking at 50% of K_Q or for a natural crack produced at liquid nitrogen temperature (-196°C) by tapping a wedge into a notch, then machining the specimen around the resulting natural crack in the desired geometry. Figure 1 indicates that the razor blade and sharp-cornered saw blade yield K_Q values very similar to those for specimens with natural or fatigue cracks. Precracks with tip radii greater than 0.1 mm yield increasing K_Q values and are not sufficiently sharp; a similar result has been reported in Ref. (3).

The values of K_Q in Figure 1 were produced at relatively high speed (25mm/s displacement rate) at -30°C. The results indicate that a razor blade precrack should be sufficiently sharp for valid K_{Ic} testing as long as the value of K_Q is not less than that in Figure 1, and the yield stress is not increased significantly. The blade precracking method would have to be reexamined if more brittle conditions were used, because a natural crack might then be sharper. Similar plots to Figure 1 were used to justify metals testing prior to the use of fatigue cracks (11). The need for a very sharp crack tip in more brittle polymers such as polystyrene has been explored in Ref. (12).

Results similar to those in Figure 1 were also obtained on Pipe E specimens, tested at -100°C and 51 mm/s. Natural cracks produced at liquid nitrogen temperature gave an average K_Q of 2.3 $MNm^{-3/2}$, while the corresponding value for blade sharpened notches was a similar 2.5 $MNm^{-3/2}$.

Rate Effects

Figures 2, 3, and 4 give the variation of several fracture parameters with displacement rate at room temperature. Specimens from each of the three pipes give similar behavior; they are sufficiently brittle for valid plane strain fracture toughness testing only at high rates. At low rates the behavior becomes completely notch insensitive, as σ_{net} approaches the yield stress. The value of σ_{net} is the maximum force divided by the cross-sectional area between notches in the DEN specimen. The value of K_Q satisfies Eq. (1) when the ratio S/c equals 1.0; this condition is indicated as "valid K_{Ic}" on the figures (since $c \simeq B$, the thickness requirement is also satisfied). As noted earlier, this does not fully correspond to the definition of a valid test in ASTM standard E399.

The DEN specimen is useful in separating notch sensitive behavior from ductile, notch insensitive behavior. Due to the symmetric placement of the notches, bending effects are minimized and the average stress on the net cross-section at fracture can be calculated. This geometry is used in a standard test of the sharp notch sensitivity of sheet materials in ASTM standard E338.

Figures 2-4 demonstrate the strong effect of rate on the fracture behavior of PVC. A change in testing speed of only one to

three orders of magnitude is needed to cover the complete range of behavior from notch insensitivity, with no effective stress concentration resulting from sharp cracks, to very brittle, valid plane strain fracture toughness response. In theory, the transitional region between these extremes is important, since there is some notch sensitivity, but not enough for the valid use of LEFM; more complex failure criteria are required. In practice this appears to be of little consequence, since any conservative design would assume the more brittle properties associated with only a moderate increase in rate. Figure 5 shows the appearance of fracture specimens covering this range, from gross yielding to a flat, brittle fracture surface with only slight whitening at the original crack border.

Fracture tests in which the rate of crack growth is controlled by specimen geometry usually show an increasing K_c for increasing crack speeds (3). The tests used in this study result in unstable crack growth, and a decreasing K_c with test speed due to a smaller yield zone at the crack tip at higher rates. In transitional cases a region of slow crack growth with a whitened appearance is observed, as in Figure 5. The whitened region at high rates when S/c=1 is very small, and corresponds approximately in size to the calculated yield zone size in plane stress, (8),

$$ r_y = \frac{1}{2\pi}(K_{Ic}/\sigma_y)^2 \tag{2} $$

From Equations (1) and (2), the value of r_y when S/c = 1 is .067c. The measured whitened zone for the tests near this condition averaged .06c. The part of the fracture surface over which the crack

growth is unstable always appears dark. The fracture toughness
measured in tests of this type is controlled by the yield zone
which develops as the load increases; no effort has been made to
determine the dynamic toughness of an unstable crack.

Specimen Size Effects

The difference between notch insensitive and K_{Ic} controlled
failure is evident in tests of specimens of different size. Fig-
ures 6-8 show the variation of the fracture parameters with the
width of DEN specimens. In each case the ratio fo crack length to
total specimen width is 0.20. The tests in Figures 6 and 7 are run
at rates where the net section strength is close to the yield stress.
The net section stress at failure is approximately constant with
specimen width, while the calculated value of K_Q increases with
size. Thus, the achievement of the yield stress on the net section
is the governing failure criterion, and the material is notch insen-
sitive in this size range. Figure 8 shows the corresponding be-
havior at a rate where K_Q satisfies the criterion for K_{Ic} in Eq. (1).
Here, the value of K_{Ic} is nearly constant with size, while the net
section strength is decreasing with increasing size, and is well
below the yield stress. Eq. (1) is still not satisfied for speci-
mens smaller than 22 mm. width (c=4.4 mm). This crack length would
represent a severe flaw in most pipes.

The results in Figures 6-8 support the use of Eq. (1) as a
test for the validity of K_Q. They also indicate the potential error
involved in running fracture toughness tests without careful con-
sideration of validity. In a TPB or CT test there is no obvious in-
dication that the material may be completely notch insensitive un-

less Eq. (1) is applied. This is particularly true for fracture surfaces which appear similar to the intermediate case in Figure 5.

Figure 9 shows little effect of specimen thickness on the value of K_Q, whether or not Eq. (1) is satisfied for the thickness condition $(S < B)$. These specimens were prepared by machining away the surfaces, leaving the desired thickness in the middle of the flattened pipe wall. The minimum thickness used is still greater than twice the plane stress yield zone size, where the strongest thickness effects are observed (3).

Conclusions

The results presented here support the use of linear elastic fracture mechanics when validity criteria similar to those used for metals are applied. Failure to consider test validity may yield meaningless results in many cases. Razor blade precracking produces acceptable crack tips under these test conditions. The room temperature behavior of PVC specimens in the size range tested varies from notch insensitive to K_{Ic} controlled when the displacement rate is varied by 2-3 orders of magnitude.

ACKNOWLEDGEMENT

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Table 1

Commercial Pipes From Which Specimens Were Taken

Pipe	External Diameter (mm)	Thickness (mm)	Material Designation*
A	274	10.1	1120
B	167	7.5	1120
C	100 (Batch 1)	9.5	1120
D	84	8.3	1120
E	324	13.3	1120
F	100 (Batch 2)	9.4	1120

* Plastics Pipe Institute of the Society of the Plastics Industry.

Table 2

Specimen Geometry

Double-Edge-Notched (DEN) Tension:

 5.1 cm wide, 15.2 cm gage length, 1.0 cm crack length.

Three-Point-Bend (TPB):

 10.2 cm span, 2.5 cm width, 1.3 cm crack length.

Thickness: Thickness is as given in Table 1 unless noted.

FIGURE 1.

LOG LOG PLOT OF CRACK TIP RADIUS vs. CALCULATED FRACTURE
TOUGHNESS, PIPE F, TPB SPECIMEN, −30°C, 25 mm/s.
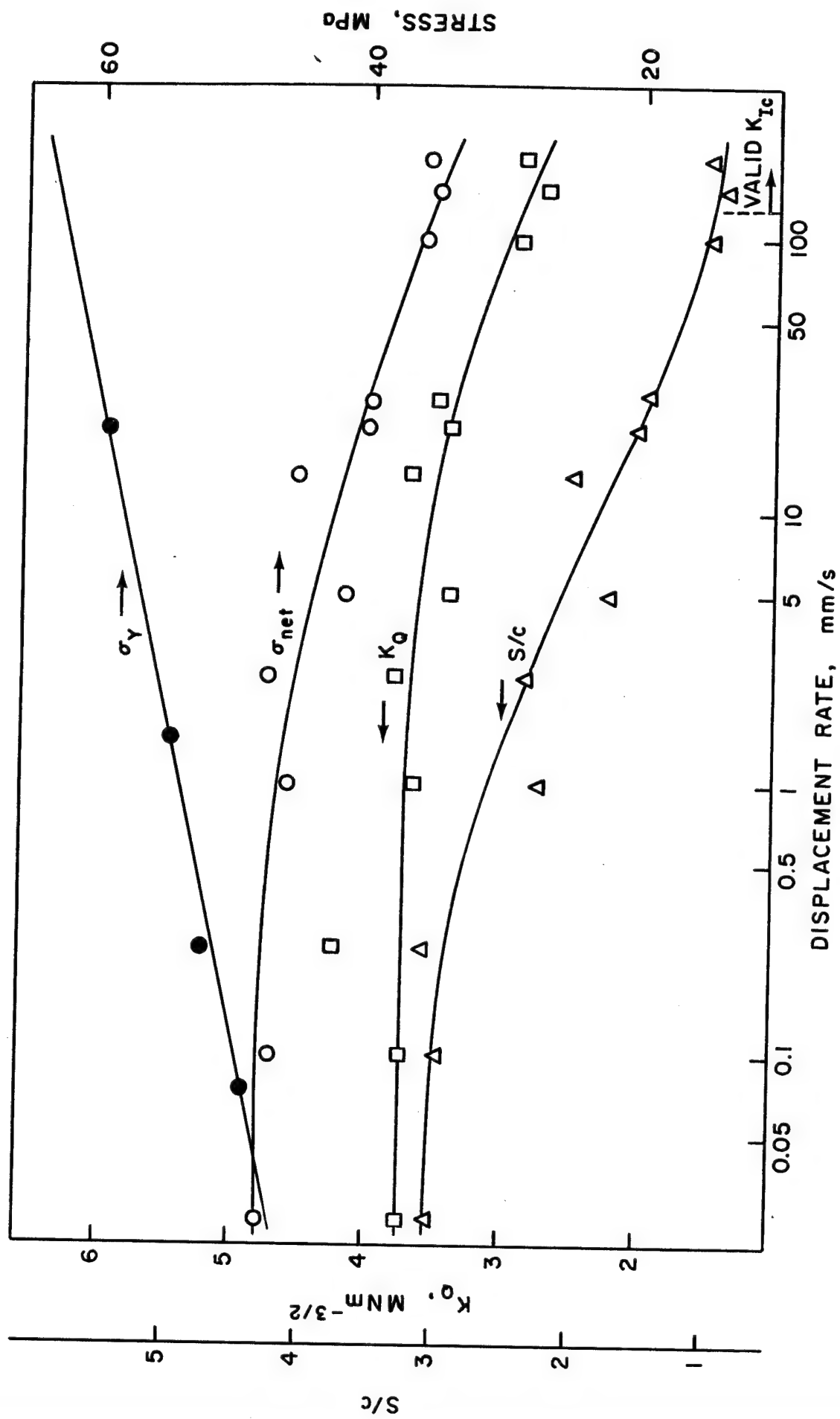
FIGURE 2.

EFFECT OF DISPLACEMENT RATE ON FRACTURE
OF PIPE C, DEN GEOMETRY.
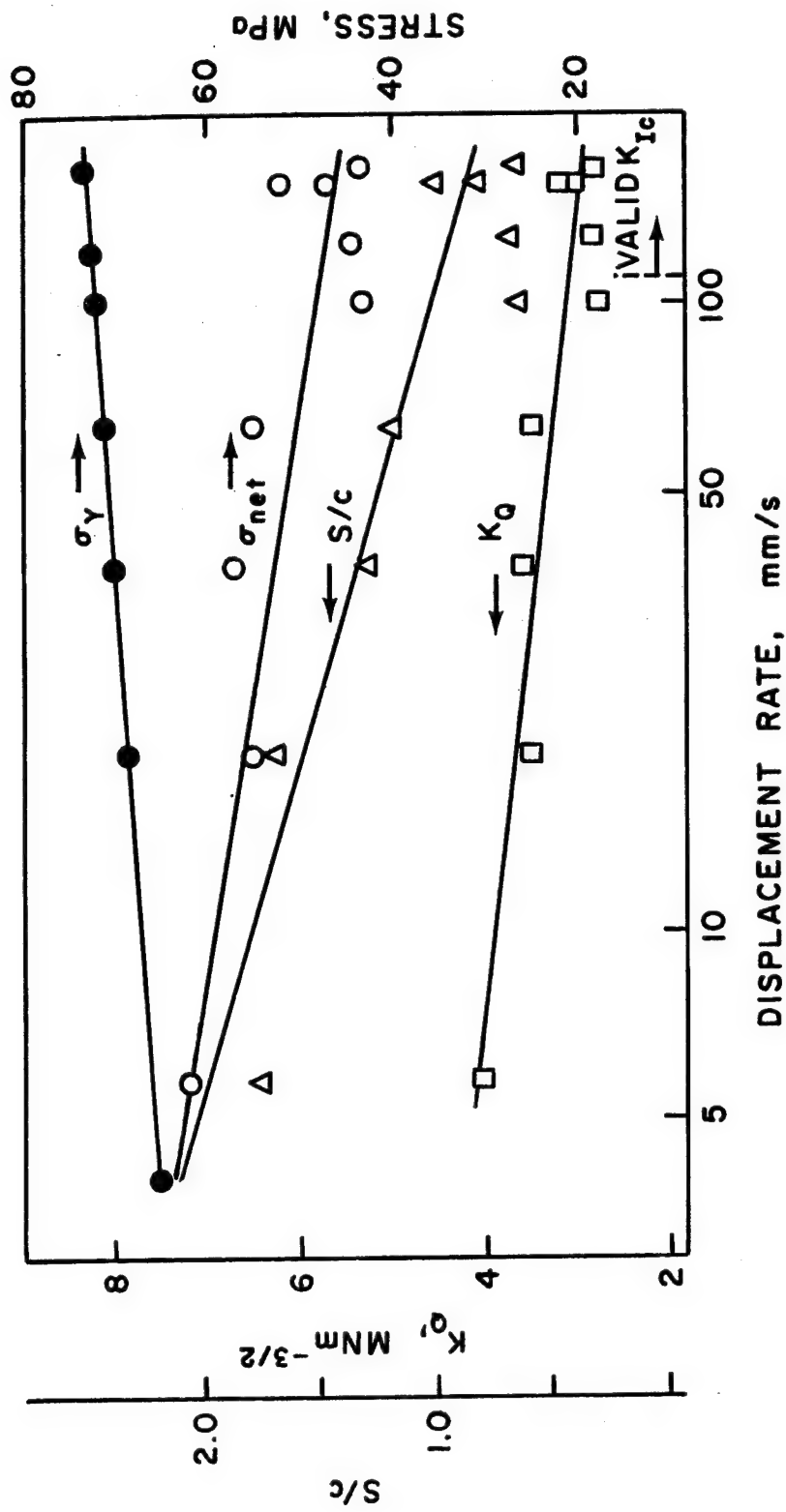
FIGURE 3.

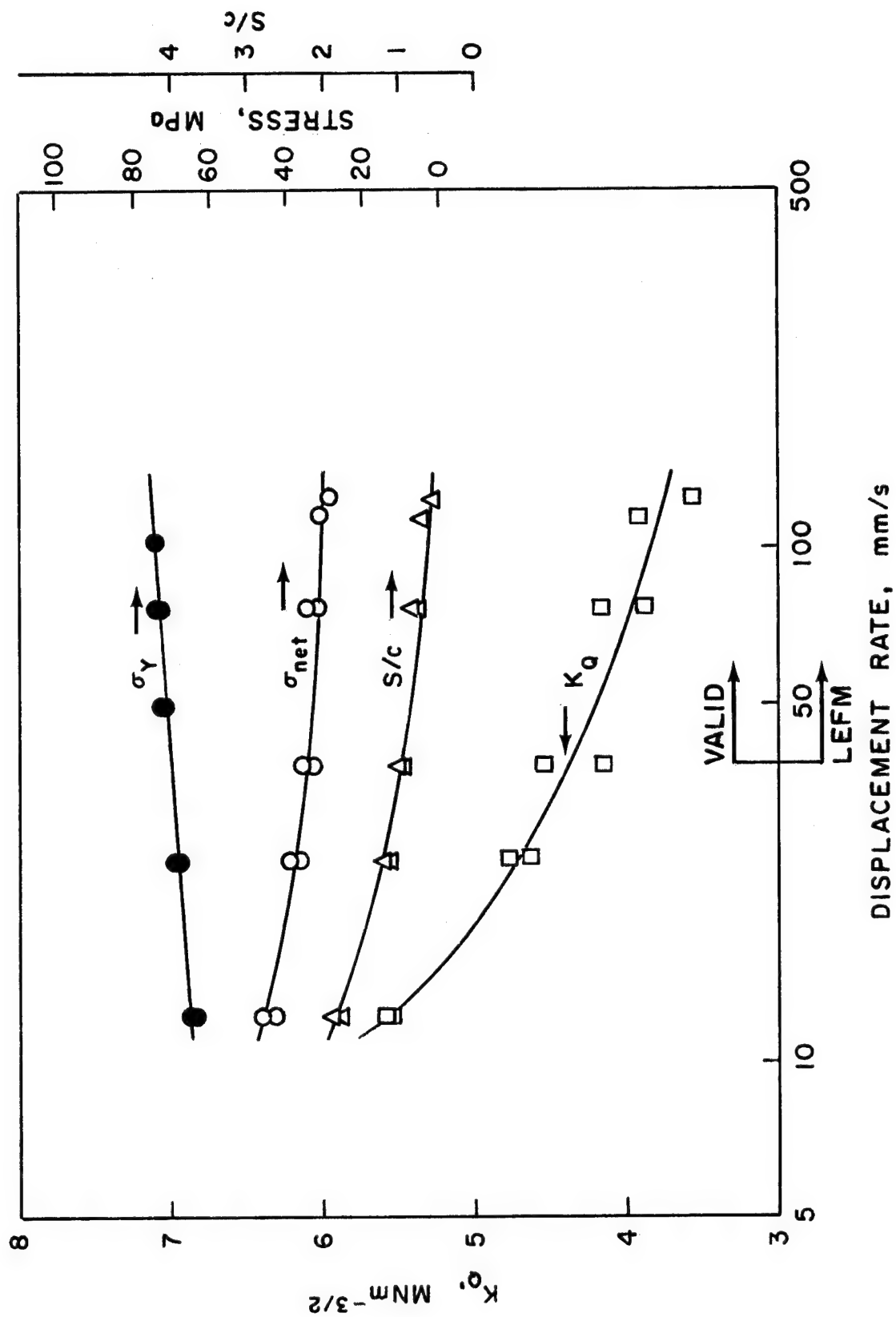EFFECT OF DISPLACEMENT RATE ON FRACTURE OF PIPE D, DEN GEOMETRY.

FIGURE 4.

EFFECT OF DISPLACEMENT RATE ON K_Q AT ROOM
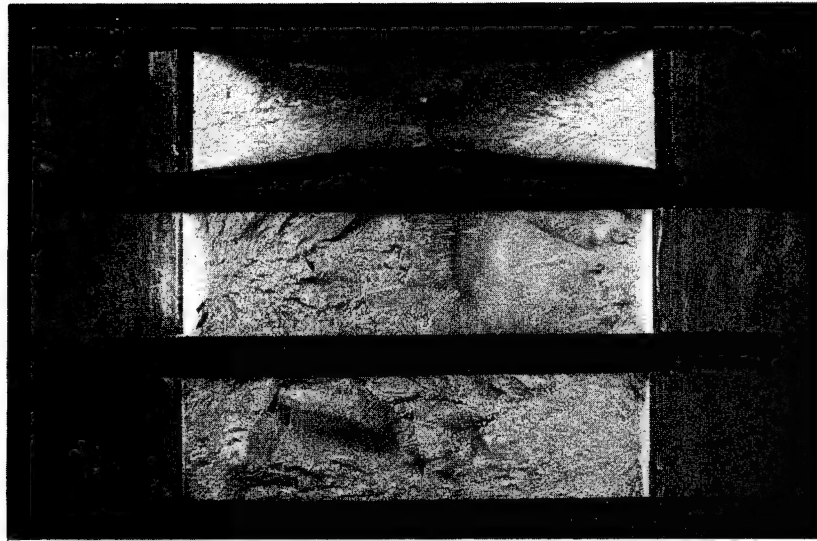TEMPERATURE ON PVC PIPE E, DEN GEOMETRY.

FIGURE 5.

FRACTURE SURFACES OF 5 cm WIDE DEN SPECIMENS
SHOWING, FROM TOP TO BOTTOM, FULLY DUCTILE,
TRANSITIONAL, AND BRITTLE (VALID K_{Ic}) BEHAVIOR.
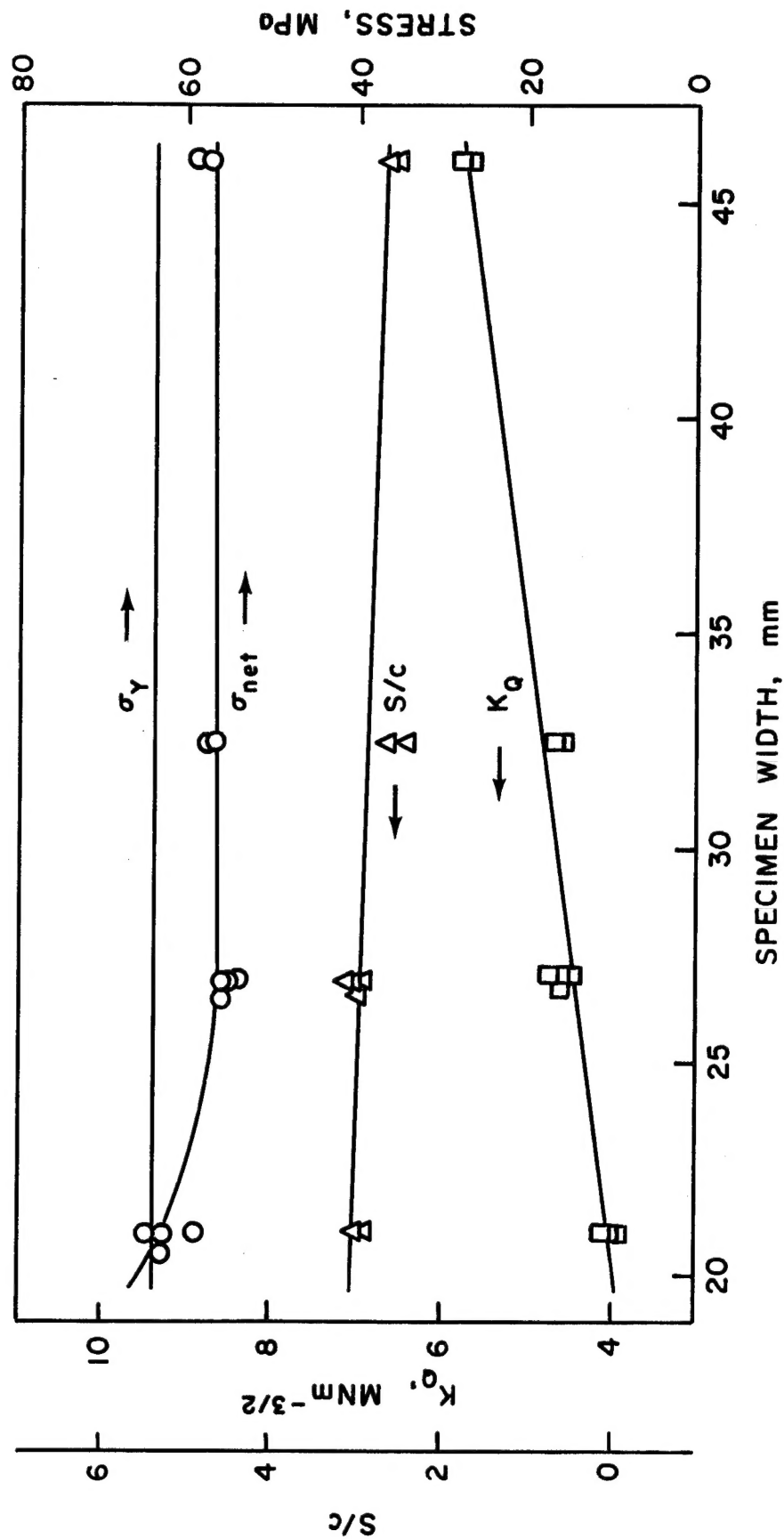
FIGURE 6.

EFFECT OF SPECIMEN WIDTH ON FRACTURE OF PIPE A,
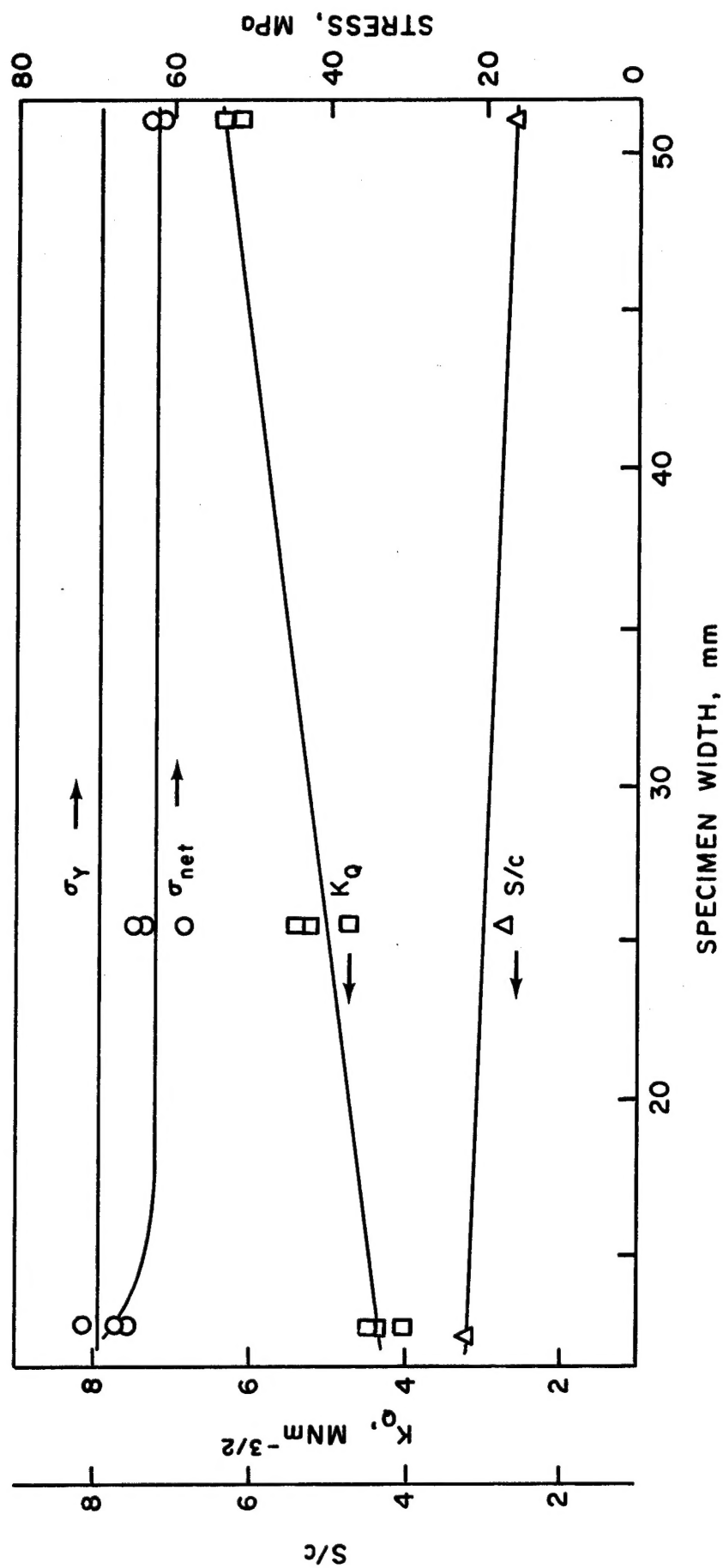DEN SPECIMEN, DISPLACEMENT RATE = 5.6 mm/s.

FIGURE 7.

EFFECT OF SPECIMEN WIDTH ON FRACTURE OF PIPE B,
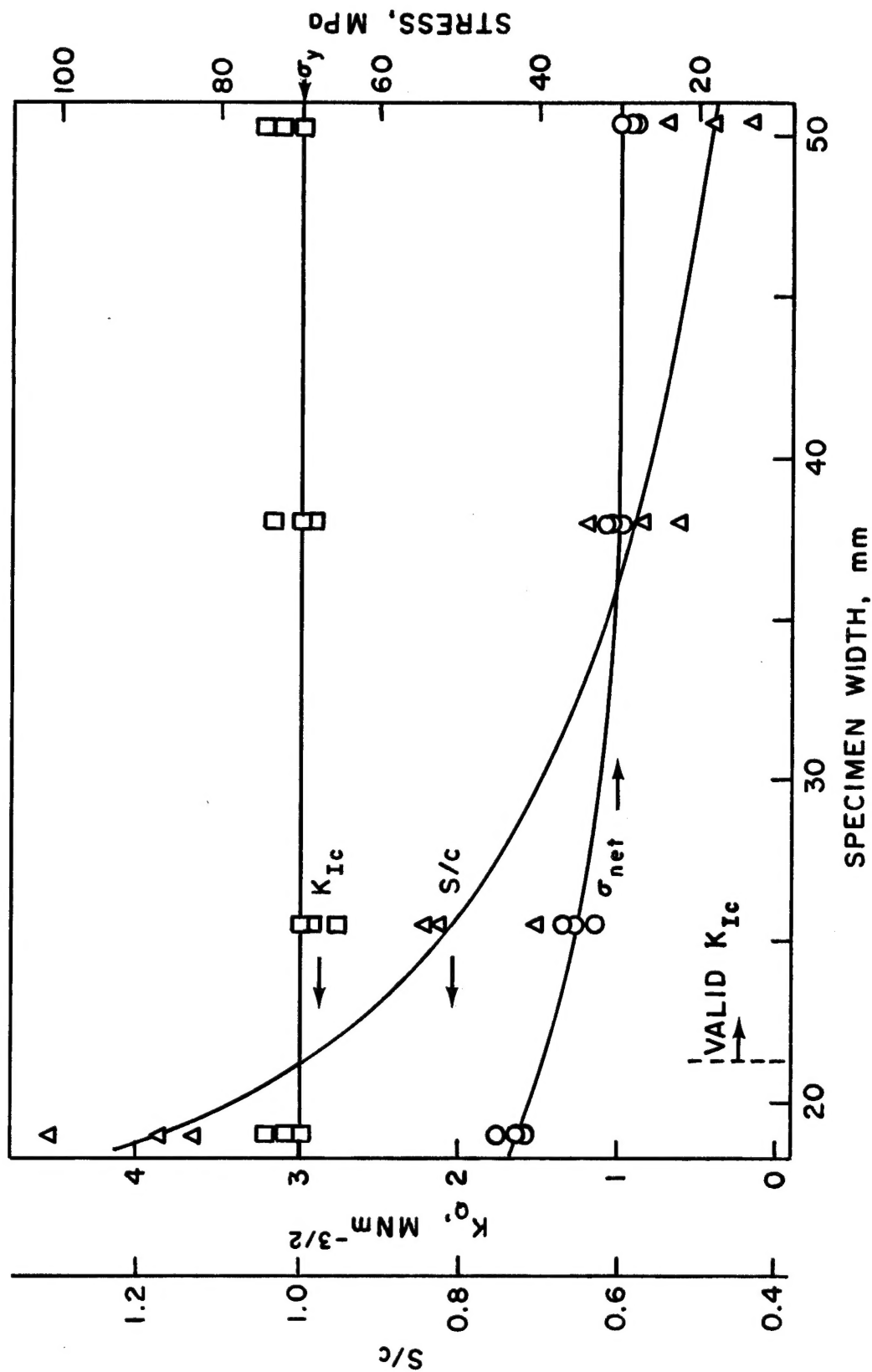DEN SPECIMEN, DISPLACEMENT RATE = 51 mm/s.

FIGURE 8.

EFFECT OF SPECIMEN WIDTH ON FRACTURE OF PIPE C,
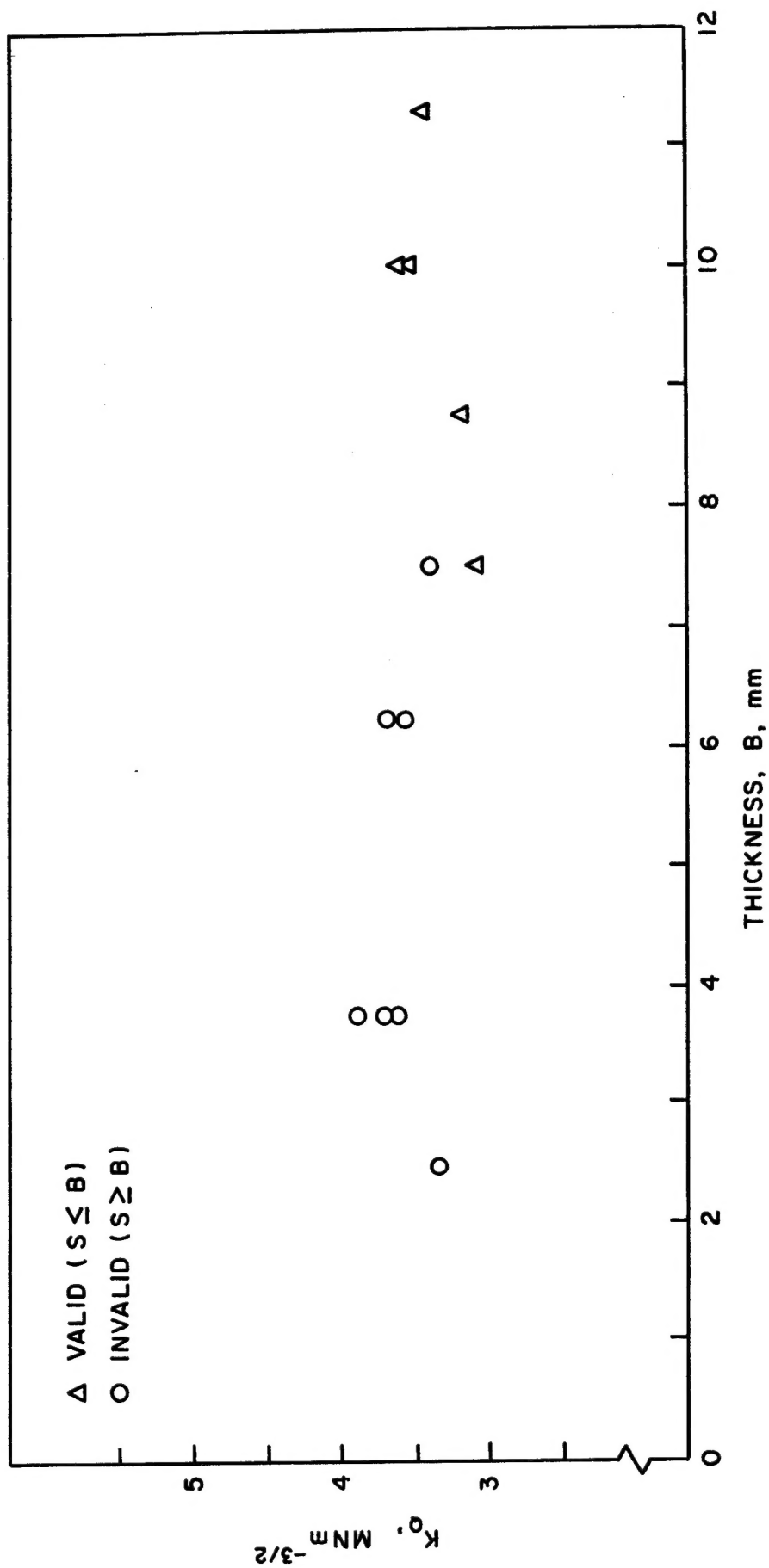DEN SPECIMEN, DISPLACEMENT RATE = 165 mm/s.

FIGURE 9.

EFFECT OF THICKNESS ON FRACTURE TOUGHNESS OF PVC PIPE E AT ROOM TEMPERATURE, DISPLACEMENT RATE 51 mm/sec., DEN GEOMETRY.